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RESEARCH ARTICLE

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Peatland carbon stocks and burn history: Blanket bog peat core evidence highlights charcoal impacts on peat physical properties and long-term carbon storage

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Peatlands are globally important carbon stores, yet both natural and human impacts can influence peatland carbon accumulation. While changes in climate can alter peatland water tables leading to changes in peat decomposition, managed burning of vegetation has also been claimed to reduce peat accumulation. Particularly in the UK, blanket bog peatlands are rotationally burned to encourage heather re-growth on grouse shooting estates. However, the evidence of burning impacts on peat carbon stocks is very limited and contradictory. We assessed peat carbon accumulation over the last few hundred years in peat cores from three UK blanket bog sites under rotational grouse moor burn management. High resolution (0.5 cm) peat core analysis included dating based on spheroidal carbonaceous particles, determining fire frequency based on macro-charcoal counts and assessing peat properties such as carbon content and bulk density. All sites showed considerable net carbon accumulation during active grouse moor management periods. Averaged over the three sites, burns were more frequent, and carbon accumulation rates were also higher, over the period since 1950 than in the period 1700–1950. Carbon accumulation rates during the periods 1950–2015 and 1700–1850 were greater on the most frequently burnt site, which was linked to bulk density and carbon accumulation rates showing a positive relationship with charcoal abundance. Charcoal input from burning was identified as a potentially crucial component in explaining reported differences in burning impacts on peat carbon accumulation, as assessed by carbon fluxes or stocks. Both direct and indirect charcoal impacts on decomposition processes are discussed to be important factors, namely charcoal production converting otherwise decomposable carbon into an inert carbon pool, increasing peat bulk density, altering peat moisture and possibly negative impacts on soil microbial activity. This study highlights the value of peat core records in understanding management impacts on peat accumulation and carbon storage in peatlands.

KEYWORDS
bulk density, burn history, carbon stocks, charcoal, fire, peat accumulation, peatland management, peatlands

1 | INTRODUCTION

Globally, peatlands contain around 30% of all soil organic carbon (SOC), despite covering only 3% of the land surface (Parish et al., 2008). In the northern hemisphere circumpolar region it is the generally low temperatures, high water-table depth, high peat moisture, and the resulting slow decay rates of net primary production (NPP) which allow peat to form. Crucially, this slow decay with very limited soil mixing (no meaningful bioturbation or cryoturbation, apart from in permafrost soils) results in annual peat cohorts. The cohorts provide an archive of peatland development (i.e., preserving layered plant and biota remains) alongside pollution traces used for dating such as spheroidal carbonaceous particles (SCPs) that can be used to reconstruct past vegetation, climate conditions and peatland events such as fires over time, providing key information on how peatlands respond to changes in climate and management. Considering the importance of peatlands in the global carbon (C) cycle, it is surprising that global C-coupled climate models still do not adequately represent peatlands (Wu & Roulet, 2014). A better process-level understanding of climate (e.g., Davidson & Janssens, 2006) and management (e.g., Evans et al., 2014) impacts on peatland SOC cycling is clearly needed since the mineralisation of peatland soil organic matter (SOM) has the potential to release vast amounts of previously locked-up C into the atmosphere (as outlined in Heinemeyer et al., 2010; e.g., Yu et al., 2001).

Blanket bogs are a globally rare peatland habitat, with the UK accounting for about 15% of the global total (Tallis, 1998). Most peatland sites in the UK are classified as being in a degraded state (Natural England, 2008), partly due to management (e.g., drainage) impacts. In fact, only about 12% of protected blanket bog sites are classified as in favourable condition (Natural England, 2008). In the UK, 90% of all peatlands are blanket bogs (Bain et al., 2011), which are often managed for red grouse (*Lagopus lagopus scotica*) shooting, commonly supported by draining the peat and regular burning of vegetation to encourage ling heather (*Calluna vulgaris*).

Burning on blanket bogs has been highlighted as having potential negative impacts on many of the peatland ecosystem services such as water storage, drinking water quality provision, flood prevention and C storage (Evans et al., 2014). However, there is only sparse literature on the effects of burn management on actual C accumulation rates in blanket bogs (Davies et al., 2016). According to Evans et al. (2014) there is only one major UK study investigating rotational burn impacts on C stocks, and this shows significantly reduced peat C accumulation on experimentally burnt compared with unburnt heather-dominated blanket bog, simulating grouse moor management (Garnett et al., 2000). However, the Garnett et al. (2000) study contains some potential methodological issues and one study is unlikely to be conclusive, especially from artificial (i.e., experimental) plots. For example, none of the depth profiles in Garnett et al. (2000) show the expected SCP peak around 1975, nor do the reported charcoal layers agree with the oldest burn date (i.e., the onset of the experimental burn rotation in 1954 on all plots). Together, these uncertainties mean that the peat C accumulation rates may have been more similar between burnt and unburnt plots than was suggested by Garnett et al. (2000). In fact, another study by Ward et al. (2007) on the same site as Garnett's study (i.e., Moor House), which was not included by Evans et al. (2014), showed equally high C accumulation on burnt and unburnt plots over the top 1 m of peat (based on coarse sampling at 10 cm depth increments). Moreover, the burn plots were artificial (i.e., not part of a real grouse moor) and the managed plots were fairly small (30 × 30 m). However, the plots offered comparable grazing impacts to this study with, for English uplands, representative low sheep grazing levels (see Section 2). As pointed out by Brown et al. (2015), fires on such small experimental areas might not represent real burn rotation impacts (i.e., often burn patches are about 50 × 100 m and a 10-year burn rotation is considered very frequent). Therefore, a reassessment of this method is urgently required in a real grouse moor context to provide more evidence concerning long-term burn rotation impacts on peat C accumulation.

Several peatland models of varying complexity and feedback mechanisms have been developed (Baird et al., 2012; Bauer et al., 2003; Clymo, 1984; Frolking et al., 2010; Gignac et al., 1991; Heinemeyer et al., 2010), which have often been compared with measured C stocks. However, there is still a surprising lack in both understanding and process-level representation of potential management-related impacts on peatland SOC cycling and other ecosystem services (Evans et al., 2014). Particularly, the evidence in relation to rotational burning as part of grouse moor management is very weak and impacts are often unclear or contradictory (Harper et al., 2018). Moreover, the potential of charcoal to "lock away" C over time, as suggested by Clay et al. (2010), could explain the observed discrepancies in peatland C sequestration between flux and stock approaches as highlighted by Ratcliffe et al. (2017). Put simply, while burning causes considerable loss of above-ground C during combustion, it also transforms otherwise decomposable biomass into charcoal, which is very recalcitrant to decomposition (Leifeld et al., 2017) and possibly also supresses microbial activity (Lu et al., 2014). Although rotational burning on grouse moors is a UK-specific issue, the impact of burning and fires on C stocks is of global importance as highlighted by the recent findings of charcoal accumulation in drained peatlands with fire history in general (Leifeld et al., 2017). However, while Leifeld et al. (2017) observed a positive relationship between charcoal/SOC ratios and soil depth, they did not include sites with controlled burn rotation management (e.g., grouse moors) nor did they report detailed (i.e., layered) comparisons for bulk density data. Bulk density is a crucial parameter for estimating C stocks and also regulates peat hydrology (water-holding capacity). Therefore, outstanding yet fundamentally important questions remain regarding controlled burn rotation impacts on long-term peat C accumulation in relation to physical properties (i.e., bulk density) and C content. Crucially, peat cores can provide the required unique insight into relating peat C accumulation and stocks not only to climatic records but also to burn management as past burn events are detectable by charcoal layers alongside changes in peat properties (i.e., bulk density).

Here we conducted a peat core study at three UK grouse moor sites under long-term burn rotation to (1) reassess previous findings from controlled plot experiments claiming C losses by burning (i.e., Garnett et al., 2000) in a real burn management context, and (2) relate long-term C accumulation rates and peat properties (as done by Leifeld et al., 2017) to past burn frequencies. We assessed two hypotheses:

1. While burning decreases SOC input (loss from litter combustion), it increases bulk density (i.e., higher charcoal content).
2. Peat C accumulation relates positively to higher burn frequencies as determined by charcoal layers and largely in relation to increased bulk density.

2 | MATERIALS AND METHODS

2.1 | Site locations

The three study sites were all located in north-west England and the names used to identify the sites throughout this report are Nidderdale, Mossdale and Whitendale (Figure 1).

Each site is an actively managed grouse moor with low sheep stocking densities of less than 0.5 ewes per ha and offered a rotationally burnt catchment of similar size (~10 ha). The sites were chosen based on a set of key criteria: all were classed as degraded (i.e., heather dominated and past drainage and current burn rotation) blanket bog with a mean peat depth of over 1 m, and were managed as grouse moors. Nidderdale, Mossdale and Whitendale had an average slope at

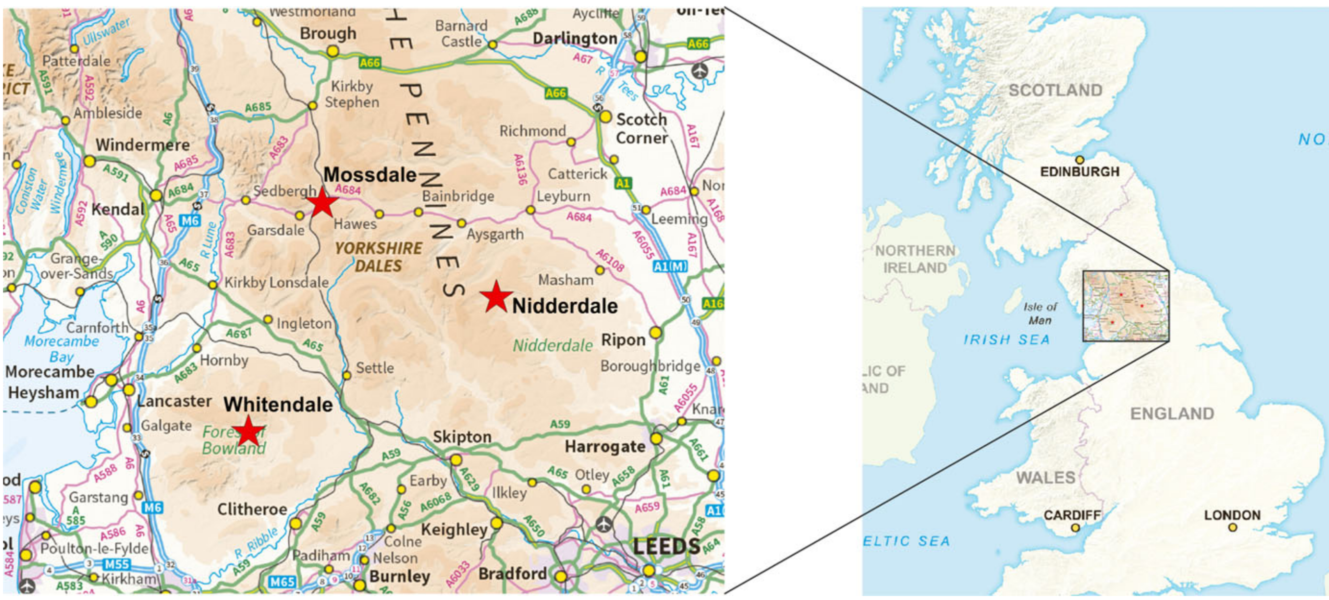

FIGURE 1 Field site locations in north-west England (inset) in relation to the UK (outline). Shown are the three sites Nidderdale, Mossdale and Whitendale (indicated by the red stars). Maps downloaded on 9 September 2016 from MiniScale (TIFF geospatial data) during download of GB tiles (updated 3 December 2015) from Ordnance Survey (GB) using the EDINA Digimap Ordnance Survey Service (http://digimap.edina.ac.uk).

the experimental plots (measured using a 1.5 m long spirit level on a 4 m long wooden plank and representative of the slope across a length of about 50 m) of 3°, 10° and 6°, respectively. Typically, the sites were managed with a 10–15-year burn rotation (based on gamekeeper information) and all had a long history of burning (more than 100 years; based on estate information); most likely burn rotations were part of the management from about 1850 onwards, similar to Moor House as described by Garnett (1998). Figure 2 shows ground-level pictures of all three sites.

All sites had more than 50% ling heather (*Calluna vulgaris*) cover, with at least some existing bog vegetation in the form of cotton-grass (*Eriophorum* spp.) and *Sphagnum* moss species (with most *Sphagnum* spp. cover at Mossdale). National vegetation classification (NVC) categories were determined for each site in 2012 using the MAVIS software (DART Computing & Smart, 2014). Overall, the MAVIS software classified all plots at all sites as the NVC category M19a, which is the *Erica tetralix* sub-community of the *Calluna vulgaris–Eriophorum vaginatum* blanket mire community.

While two of the sites had some old and mostly infilled drainage ditches (also called grips) at low density, the third site (Whitendale) without grips included some natural gullies (also mostly revegetated and infilled). The following specific site information was based on a five-year (2012–2016) study period (Heinemeyer et al., forthcoming[1]) with hourly weather data (MiniMet AWS, Skye Instruments Ltd, Llandrindod Wells, UK), six-hourly readings from water table depth meters (WT-HR 1000; TruTrack, New Zealand) placed inside dipwells in areas of tall heather (last burnt about 15–20 years ago), and manual peat depth assessment in 2012 using commercial (Clarke CHT640) 1.5 cm diameter PVC drainage rods consisting of 92 cm extendable sections with screw fittings (i.e., pushing rods into the peat until detectable resistance of the bedrock/clay layer). The following section provides a basic summary for the three sites, including climatic, hydrological and soil conditions, and locations are shown in Figure 1.

Nidderdale is located on the Middlesmoor estate in upper Nidderdale, which lies within the Yorkshire Dales National Park, UK, at 54° 10′ 07″N; 1° 55′ 02″W (UK Grid Ref SE055747) about 450 m a.s.l. The site had a mean annual air temperature of 7.2 ± 0.5°C and annual precipitation of 1587 ± 211 mm. The mean annual water table depth was −14.6 ± 6.4 cm. The soil is a poorly draining organic peat (Winter Hill series) with an average depth of 1.6 ± 0.3 m across the experimental plot; peat depth across the catchments ranged from 0.2 to 2.9 m. Most of the grips within the study area, which were dug about 40 years ago, were naturally infilled by 2010 and no further grip blocking took place during the study period.

Mossdale is located in Upper Wensleydale within the Yorkshire Dales National Park at 54° 19′ 01″N; 2° 17′ 18″W (UK Grid Ref SD813913) about 390 m a.s.l. The mean annual air temperature was 7.2 ± 0.5°C and annual precipitation was 2,029 ± 346 mm. The mean annual water table depth was −8.1 ± 5.7 cm. The soil is a poorly draining organic peat (Winter Hill series) with an average peat depth of 1.2 ± 0.4 m at the experimental plot; peat depth across the catchments ranged from 0.3 m to 2.1 m. Most of the grips within the study area, which were dug about 40 years ago, were naturally infilled by 2010.

Whitendale is located within the Forest of Bowland (an Area of Outstanding Natural Beauty), Lancashire, at 53° 59′ 04″N; 2° 30′ 03″W (UK Grid Ref SD672543) about 410 m a.s.l. The mean annual air temperature was 7.6 ± 0.5°C and annual precipitation was 1,858 ± 308 mm during the five-year study period. The mean annual water table depth was −8.7 ± 6.9 cm. The soil is a poorly draining organic peat in the Winter Hill series with an average peat depth of 1.7 ± 0.4 m at the experimental plot; peat depth across the entire catchment area ranged from 0.2 m to 4.5 m. This study area had no grips, although gullies (similar to grips but naturally formed) were present in both catchments.

FIGURE 2 Site conditions as observed by ground-level pictures (credit A. Heinemeyer) taken in winter 2012 at each site (Nidderdale, Mossdale and Whitendale). Note the burn areas with re-growing sedge cover (mostly cotton-grass, *Eriophorum* spp.) on the otherwise heather-dominated blanket bog vegetation.

2.2 | Peat sampling

Peat samples were taken using a manual 1.1 m box corer. At all three sites, 1 m depth (5 × 5 cm diameter) peat cores were taken twice after burning in March 2013 from within a 5 m radius located within one experimental burn area (ca. 30 × 70 m), two adjacent ones (within 0.5 m) in early April 2016 (set 1) and one in late March 2017 (set 2) to supplement peat property data. Peat cores were transferred in the field into a three-sided square ducting and contained by the cover lid for transport to cold storage in a fridge and then freezer. The top 25 cm of the peat profile was analysed for dating and peat property analysis, specifically C content (C_{org}), bulk density (BD), and macro charcoal fragments (>120 μm particle size).

2.3 | Peat core dating

Peat core dating was done (for both cores from set 1) based on counting SCPs and relating it to the onset of fossil fuel driven industry and the onset of clean air technology, resulting in a peak-shaped SCP distribution (e.g., Swindles, 2010).

Spheroidal carbonaceous particles were analysed according to Swindles (2010) with some adaptations (as outlined below) due to the specific nature of the peat. Contiguous 2 cm^3 subsamples of the paired peat cores from each site were taken to a depth of 16 cm (below the depth of SCP onset for all sites) at 0.5 cm resolution. A saw and a chisel were used to sample from the frozen cores and the dimensions of the resulting gap (e.g., for volume determination) were measured with a Vernier calliper (see De Vleeschouwer et al., 2010). The samples were dried for 24 hours at 105°C and 0.1 g of dried sample was then prepared using an acid digestion in 30 ml of concentrated nitric acid (HNO_3), which was left for 24 hours at room temperature before being put on a hot plate at 140°C for up to 10 hours (until the solution was reduced to approximately 5 ml and all organic material had dissolved). Subsequently 10 ml of deionised water was added and the suspension was transferred to a 15 ml polypropylene centrifuge tube for centrifuging at 1,500 rpm for five minutes. The supernatant was decanted into a sink and the residue was washed twice more with deionised water, centrifuged and the supernatant decanted. The final residue (~15 ml or less) was decanted into a small centrifuge tube and as much water as possible was removed using a Pasteur pipette (the remaining sample weight was determined). A small quantity of the liquid residue (a drop) was removed and placed on a coverslip (the remaining sample residue was weighted again to determine the actual sample weight analysed for SCPs). The coverslip was left in a fume hood overnight to evaporate all water. A known quantity of the final solution was mounted on 22 mm rectangular slides using Histomount. SCPs were counted under a light microscope at ×400 magnification and expressed as #/gDM (i.e., number of particles per gram of dry mass of peat) according to Swindles (2010). SCPs of approximately 2 μm and larger were identified based on their spheroidal three-dimensional morphology (determined by focusing in and out on the particle using a light microscope) and distinctive black colour. SCP particles are usually between 10 and 70 μm in diameter and may have a pitted or lacy surface texture (Swindles, 2010). The trace of SCPs in the cores from this study was undetectable below a depth of 15 cm.

2.4 | Peat property analyses

2.4.1 | Carbon content

Two C content (C_{org}) datasets were used (set 1 and 2). C_{org} for individual (0.5 cm) peat layers was measured for subsample sections on 0.5 × 4 cm dried section removed for BD assessment (see below) from each layer (set 1: 0–15.5 cm; set 2: 16–25 cm). Dried peat samples were manually ground up in a mortar. For each analysis, about 30 mg of the ground samples was sealed in pre-weighed tin foil capsules and run through a vario Macro C/N analyser (Elementar Analysensysteme GmbH, Hanau, Germany) according to a standard operating procedure ("Plant500"; Environment Department, University of York). Results were factored to glutamic acid standards and compared with organic material standards (i.e., blanks are empty compartments in the carousel); glutamic acid samples of 50 mg (± 0.5) provide a "daily factor" and are used to adjust the results of several daily runs against each other; a reference material of birch leaf was used at the start and end of the run (Elemental Microanalysis Ltd CatNo. B2166, C_{org} 48.09% ± 0.51%, N 2.12% ± 0.06%).

2.4.2 | Bulk density

To determine BD, 2 cm^3 contiguous subsamples at 0.5 cm resolution (set 1 and 2 as above) were cut from the cores from each site to a depth of 25 cm. A knife was used to sample sections from the fresh cores (which were waterlogged) and the volume of each section was measured by water displacement in a 20 ml measuring cylinder. Samples were dried at 105°C in 10–30 ml crucibles for a minimum of 48 hours. All peat samples were dried until a constant weight was reached and stored in a desiccator until further analysis. BD was calculated as grams of dry matter per cm^3.

2.4.3 | Macro-charcoal analysis

Peat cores (set 1) for each site (Nidderdale, Mossdale and Whitendale) were analysed for macro-charcoal content following the sieving method described by Mooney and Tinner (2011). Two cores were analysed for Nidderdale: an initial "test core" and a primary core. As both cores showed similar results, charcoal counts were averaged between the two. Contiguous 2 cm^3 subsamples at 0.5 cm resolution to a depth of 25 cm were left in a 10%–15% solution of hydrogen peroxide (H_2O_2) for a minimum of 24 hours to bleach the organic matter, allowing for counting of the charcoal particles which remain unchanged by the H_2O_2. Bleached samples were gently washed through nested sieves of two mesh sizes to capture two size fractions (>120 and >500 μm) of charcoal particles. These were counted separately on a petri dish with a coarse grid under a light microscope at ×20 magnification.

2.5 | Burn frequency estimates

Past fire frequencies were based on identifiable charcoal peaks per time period responding to grouse shooting intensity (most intense: 1950–2015; less intense: 1850–1950; pre-driven shoots: 1700–1850). For this, the latest surface burn layer marked 2013 for all sites, the SCP dating (defined by the average of set 1 for SCP peaks, their onset and decline) was used to obtain a site-specific depth corresponding to the years 1975, 1950 and 1850 (as per Swindles, 2010) and the year 1700 was assumed to be the same for all three sites (25 cm peat depth) based on dating a very similar blanket bog with similar peat depth and at similar altitude at Moor House (based on unpublished data provided by Graeme Swindles at the University of Leeds and also the unpublished PhD thesis by Garnett, 1998). Therefore, the oldest age was the most uncertain as it had to be assumed that past accumulation rates were similar across the three sites (which is likely as none of the sites were intentionally managed for grouse before 1850). If a charcoal peak occurred at an age threshold, it was counted only in the upper layer (as charcoal infiltration would have most likely resulted in a downward migration).

2.6 | Peat and carbon accumulation rates and carbon stocks

Peat accumulation across the peat profile was calculated by using the peat depth increments (over time as derived by the SCP dating method). C stocks were derived by multiplying C_{org} with the BD of the corresponding peat depth section (and adding up over depth layers); this used individual 0.5 cm sections. For C accumulation rates, C stocks per depth layer were divided by the SCP-identified time periods in years (see Section 2.5).

2.7 | Statistical analyses

All statistical analysis was performed in R (R Core Team, 2016). Differences in C stocks among the sites (three) were analysed using one-way ANOVA and Kruskal–Wallis H tests (as the data did not fulfil the ANOVA criteria of a normal distribution). Differences in C accumulation rates were analysed using two-way ANOVA and Friedman tests (as the data did not fulfil the Levene test for equality of error variances as ANOVA criteria), with data grouped into three periods defined by the onset and decline of SCPs and maximum core depth. Linear regressions were performed for the peat chemical and physical parameters against natural log-transformed charcoal count data. The adjusted coefficient of determination (adj. R^2) is reported, which corresponds to adjustments made to the R^2 based on the degrees of freedom of the respective model (adjusted to the number of regressors and the sample size).

3 | RESULTS

The patterns in BD, SCPs and C_{org} were similar for all three sites (Figure 3). There was a peak in BD of around 0.15–0.2 g/cm^3 at a depth of about 5 cm, which coincided with the highest peak in SCPs at all sites. The C_{org} showed a general increase with depth from about 49% to around 54%, but this was separated by a sudden shift at around 10 cm depth (which coincided with the SCP peak areas), where a decrease from the surface to bottom peat layers in C_{org} of about 5% was observed (Figure 3). The BD, SCP counts and C_{org} were lowest overall at Mossdale, and the SCP peaks at Mossdale and

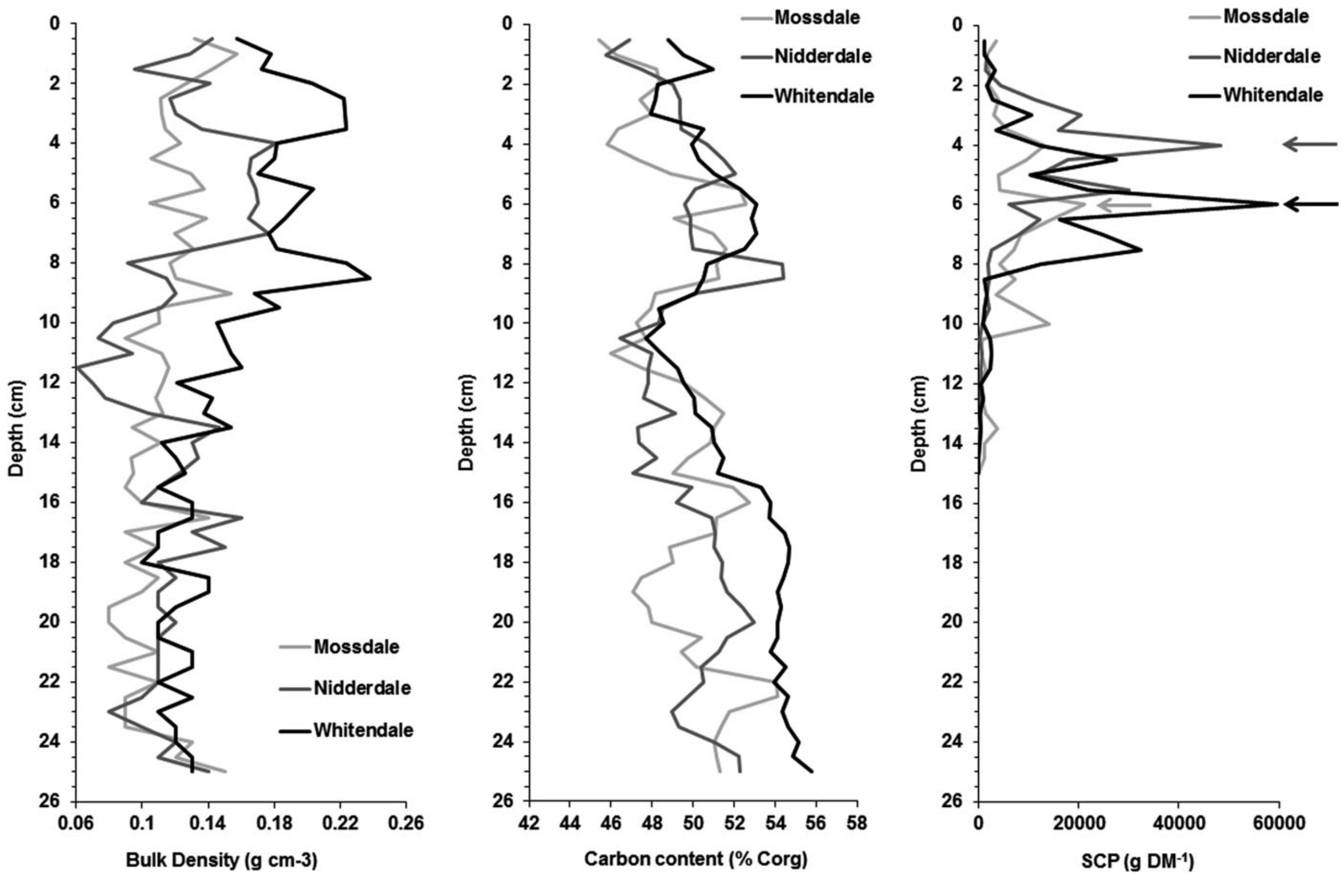

FIGURE 3 Peat core depth profile for bulk density (left), carbon content (% C_{org}) (middle) and spheroidal carbonaceous particle (SCP) counts (right) for the three sites determined in 0.5 cm sections to a depth of 25 cm (note the different *y*-axis for SCPs as these were only detected to 15 cm depth), with arrows indicating the peak SCP counts corresponding to the year 1975 (as per Swindles, 2010).

Whitendale were at 6 cm compared with 4 cm at Nidderdale. SCPs could not be detected below 14.5 cm at Mossdale, 13 cm at Nidderdale and 14 cm at Whitendale.

The layered BD, C_{org} and peat-age profile data (Figure 3) allowed calculation of C accumulation rates over time (Figure 4). Mean C accumulation rates (in g C m^{-2} $year^{-1}$ ± *SD*) over the entire top 26 cm (equal to the period 1700–2015) increased in the order Mossdale (46 ± 22), Nidderdale (50 ± 24) and Whitendale (68 ± 37).

There were clear peaks in charcoal concentration throughout the peat profile. However, peaks were larger and more frequent nearer the surface, particularly for Nidderdale and Whitendale (Figure 5).

Together with the SCP-based dating tool and the estimated age of 1700 at the maximum peat depth, the charcoal peaks (size fraction >120 μm) provided estimates of past burn frequencies (Table 1). Burn frequencies were shortest on average during the period 1950–2015 (every 17 years; 1850–1950: every 28 years; 1700–1850: every 31 years) and burns were most frequent, when averaged over the whole period since 1700, at Whitendale (every 23 years), less frequent at Nidderdale (every 25 years) and least frequent at Mossdale (every 28 years). However, the actual charcoal peaks were highest at Whitendale and Nidderdale, with very low counts for the Mossdale site during 1850–1950 (cf. Figure 5); thus burn frequencies (and possibly intensity) for Mossdale might be less in comparison to the other two sites than the 25 years indicated for the period 1850–1950 in Table 1 as this was based on very low charcoal counts per peak.

C accumulation rates were not normally distributed but both parametric and non-parametric tests on the natural log-transformed data resulted in the same statistical differences (only the non-parametric results are reported). The C accumulation rates (mean ± *SD*), based on BD and C_{org} for the individual, management-related SCP dated sections (Figure 6), were significantly ($p < 0.001$) higher (87 ± 32 g C m^{-2} $year^{-1}$) during the most recent period (1950–2015) compared with 1850–1950 (38 ± 11 g C m^{-2} $year^{-1}$) and 1750–1850 (43 ± 8 g C m^{-2} $year^{-1}$). While the C accumulation rates in the two most recent periods were significantly higher ($p = 0.001$) at Whitendale than at Mossdale or Nidderdale, rates were significantly higher ($p < 0.001$) at both Nidderdale and Whitendale than at Mossdale during the oldest period.

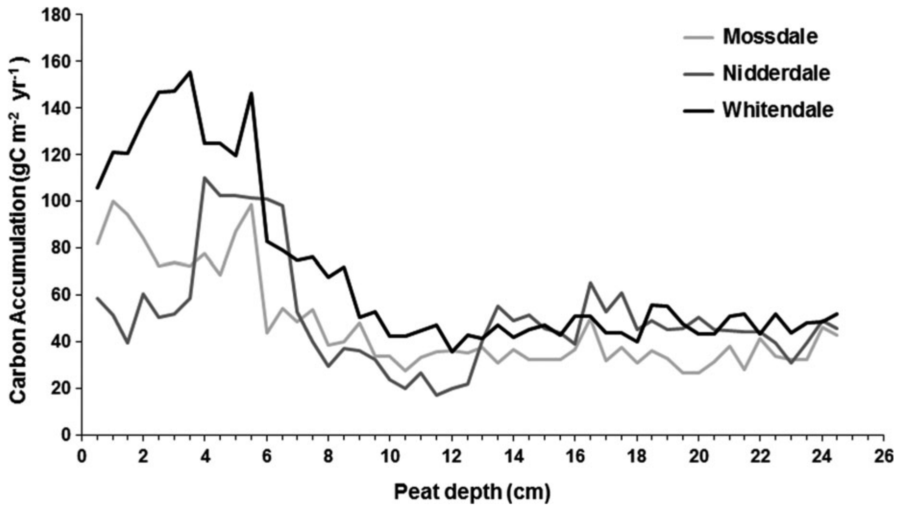

FIGURE 4 Annual peat carbon (C) accumulation rates derived from data in Figure 3 (i.e., bulk density, C content and spheroidal carbonaceous particle age-depth profile data) for the three sites.

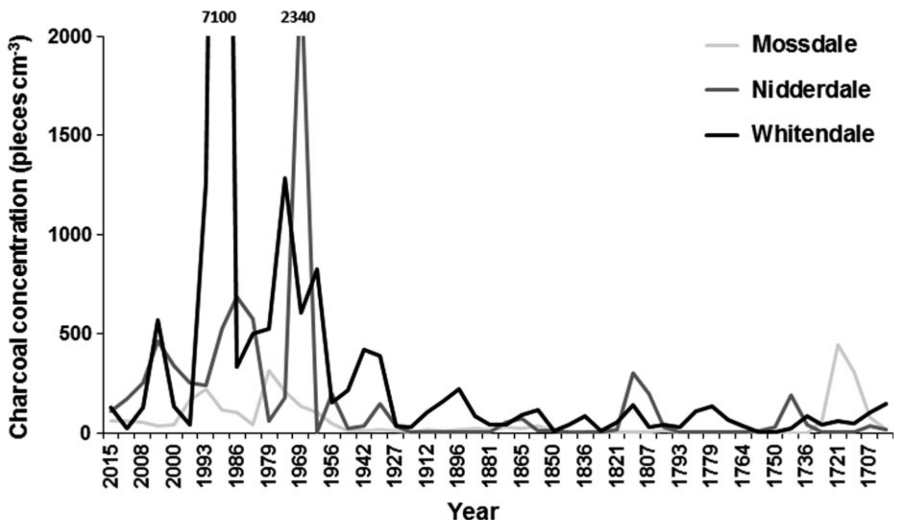

FIGURE 5 Charcoal concentrations (with a size fraction of >120 μm) through the peat core depth profile for the three sites, determined for each 0.5 cm section to a depth of 25 cm but shown as the year each depth relates to (based on spheroidal carbonaceous particle peat core dating over the top 15 cm and assuming an age of ca. 300 years (i.e. dating from 1700 A.D.) at 25 cm based on data by Garnett, 1998). The *y*-axis is truncated to allow peak identification (the maximum values are given where peaks are cut off).

The peat core analysis revealed several positive relationships in the chemical and physical peat properties and the charcoal concentration, which were consistent between sites, but the regressions became less robust (the margin of statistical uncertainty was larger) when using fewer data (i.e., going from all sites to individual sites and from the entire 25 cm core to only the top 15 cm layer). However, all peat and peat C accumulation rates showed strong multimodal distributions and thus the linear regression analyses lose some statistical robustness and the below data and regression results are mainly reported to offer a comparison to other studies.

Over the top 15 cm, the three sites revealed significant (see Table 2) correlations between BD, C_{org}, peat and C accumulation rates, and natural–log transformed charcoal concentrations (Figure 7). Importantly, the greatest impact overall was observed for BD (Figure 7a; Table 2), which reflected the strong relationships at the overall most frequently burnt sites with higher charcoal counts at Nidderdale and Whitendale (Figure 7b). However, whereas BD and C accumulation rates showed a fairly strong (adj. R^2 ~0.4) positive relationship with charcoal piece abundance, C_{org} showed a generally very weak (adj. R^2 ~0.1) positive relationship. Moreover, the R^2 values for the various regressions against the natural log-transformed charcoal concentrations were overall highest for Nidderdale (see Table 2). Most likely this improved regression fit

TABLE 1 The estimated burn frequencies per site, period and overall based on charcoal (>120 μm size) peak frequencies. Specified periods (based on spheroidal carbonaceous particle dating) reflect average periods of different management intensity (i.e., onset of grouse management in 1850 and general intensification from 1950). Standard deviations (±) are also provided for the 1950–2015 and overall site means.

Burn frequency	1950–2015	1950–2015	Overall mean per site
Mossdale	22		Mossdale: 28 ± 8
Nidderdale	16	17 ± 4	Nidderdale: 25 ± 9
Whitendale	13		Whitendale: 23 ± 9
Burn frequency	**1850–1950**	**1850–1950**	
Mossdale	25		
Nidderdale	33	28 ± 5	
Whitendale	25		
Burn frequency	**1700–1850**	**1700–1850**	
Mossdale	38		
Nidderdale	25	31 ± 6	
Whitendale	30		

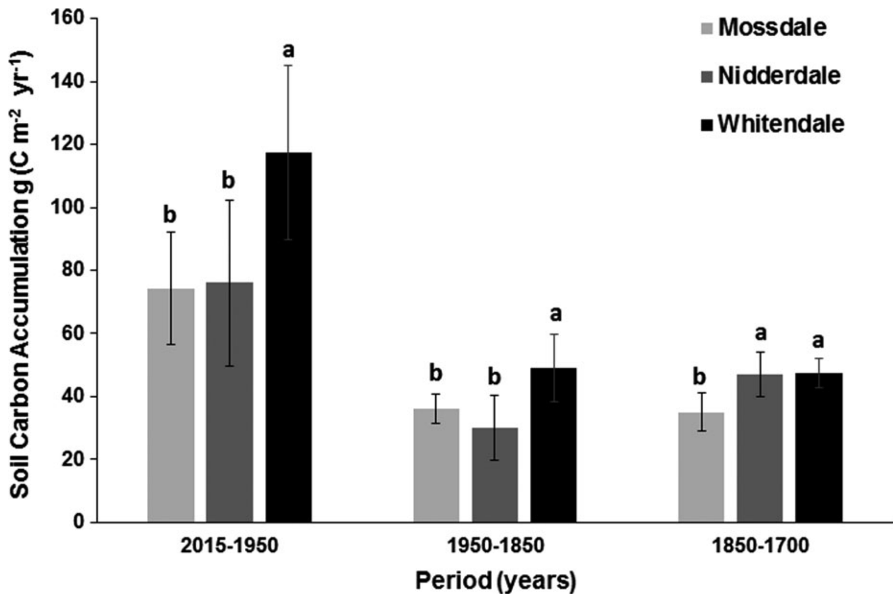

FIGURE 6 Soil carbon accumulation rates, based on spheroidal carbonaceous particle dating of the peat cores together with detailed bulk density and organic carbon content from the 0.5 cm peat depth layers. Mean (±*SD*) rates were calculated for each site for separate periods, reflecting approximate times of management changes (i.e., onset of grouse moor management in 1850 and intensification from 1950). Accumulation rates differed significantly (indicated by different letters for each period) between sites in all three periods (2015–1950: $p = 0.001$; 1950–1850: $p < 0.001$; 1850–1700: $p < 0.001$).

was related to a clearer peak distribution due to more charcoal (i.e., higher counts) with overall well defined burn peaks (Figure 5). Moreover, this high Nidderdale charcoal count possibly reflected the drier climate conditions (i.e., Nidderdale generally providing the best heather-burning conditions due to lowest rainfall of all three sites; see Section 2).

Over the entire peat depth (25 cm), the three sites also revealed significant (see Table 3) correlations between BD, peat and C accumulation rates and charcoal concentrations, but not for C_{org}. Again, the greatest impact (greater BD; Figure 8a) occurred on the overall most frequently burnt sites Nidderdale and Whitendale (Figure 8b). As observed for the top layer, BD and C accumulation rates showed an overall strong positive relationship (adj. R^2 ~0.35) with charcoal piece abundance, whereas peat accumulation showed only a weak positive relationship (adj. R^2 ~0.16) and C_{org} did not reveal any relationship (see Table 3). Moreover, the R^2 values for the natural log-transformed charcoal regressions (for C, peat accumulation and BD), were again highest for Nidderdale (see Table 3), possibly relating to the overall high burn frequency (Table 1) and charcoal concentrations (Figure 5).

TABLE 2 Peat core analysis: peat depth 0–15 cm. Regression model statistics for peat and carbon accumulation rates, carbon content and bulk density against the natural log (ln) transformed charcoal concentrations over the top 15 cm peat core section (equal to the period 1850–2015) for 0.5 cm section samples (i.e., $n = 30$ per site; degrees of freedom were $n - 2$) shown in Figure 7 (either for all sites combined or the three individual sites).

x versus *y* regression parameters	*p* Value	Significance	Adj. R^2	*n*	Regression equation
All sites combined					
x(ln charcoal) ~ *y*(carbon accumulation)	<0.0001	***	0.35	90	$y = 11.838x + 14.528$
x(ln charcoal) ~ *y*(peat accumulation)	<0.0001	***	0.19	90	$y = 0.008x + 0.056$
x(ln charcoal) ~ *y*(carbon content)	0.0007	***	0.11	90	$y = 0.401x + 47.759$
x(ln charcoal) ~ *y*(bulk density)	<0.0001	***	0.41	90	$y = 0.014x + 0.081$
Mossdale					
x(ln charcoal) ~ *y*(carbon accumulation)	<0.0001	***	0.42	30	$y = 13.170x + 6.823$
x(ln charcoal) ~ *y*(peat accumulation)	<0.0001	***	0.43	30	$y = 0.020x + 0.024$
x(ln charcoal) ~ *y*(carbon content)	0.8535	NS	–0.03	30	$y = 0.061x + 48.706$
x(ln charcoal) ~ *y*(bulk density)	0.0724	NS	0.08	30	$y = 0.005x + 0.100$
Nidderdale					
x(ln charcoal) ~ *y*(carbon accumulation)	<0.0001	***	0.41	30	$y = 8.511x + 20.607$
x(ln charcoal) ~ *y*(peat accumulation)	0.0002	***	0.38	30	$y = 0.007x + 0.057$
x(ln charcoal) ~ *y*(carbon content)	0.0441	*	0.11	30	$y = 0.350x + 47.773$
x(ln charcoal) ~ *y*(bulk density)	<0.0001	***	0.43	30	$y = 0.010x + 0.086$
Whitendale					
x(ln charcoal) ~ *y*(carbon accumulation)	0.0172	*	0.16	30	$y = 13.047x + 16.560$
x(ln charcoal) ~ *y*(peat accumulation)	0.0960	NS	0.06	30	$y = 0.008x + 0.051$
x(ln charcoal) ~ *y*(carbon content)	0.0493	*	0.10	30	$y = 0.423x + 48.088$
x(ln charcoal) ~ *y*(bulk density)	0.0032	**	0.25	30	$y = 0.013x + 0.107$

Significance boundaries were NS (non-significant), and considered significant at $^{*}p < 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$.

4 | DISCUSSION

Effects of rotational burning on heather-dominated peatlands is still a controversial issue, partly due to uncertainties around the claims of negative impacts on key ecosystem services such as water quality and C storage (Harper et al., 2018). Our study provides novel insights into ecological applications of peat core-derived burn frequency reconstructions in a real grouse moors management context. The findings highlight the value of palaeo-ecological records to allow better understanding of the effects of management on peat development as done previously by Mackay and Tallis (1996), C cycling and storage. Of particular interest is the new fine-scale age-cohort information on peat properties and charcoal content in relation to C accumulation. As highlighted by Leifeld et al. (2017) for fire impacts on pyrogenic C content and C storage in northern peatlands, this fine detail on ecosystem charcoal inputs provided novel insights into potential positive long-term burn management impacts on soil C storage. However, although the present study reports findings for blanket bog peatlands, the general link between fire impacting C storage via peat properties and pyrogenic C (i.e., charcoal) is of general concern; nearly all biomes burn naturally over longer time scales (in the order of several decades to a few centuries as shown for boreal forests by Kelly et al., 2016 and also summarised for peatlands by Leifeld et al., 2017) and many areas under agricultural cultivation are burnt intentionally. However, the functional role of charcoal is still little understood (Pingree & DeLuca, 2017) and SOC models do not include the here observed burning impacts on soil properties (i.e., bulk density), C compounds (i.e., charcoal) and thus long-term C storage. Moreover, our findings highlight that these changes have potentially important implications on C cycling via eco-hydrological feedbacks, for example on water-holding capacity due to changes in BD, but also via soil biota, potentially affecting microbial communities and decomposer activity (Lehmann et al., 2011) due to so far unknown interactions.

Burning causes gaseous nitrogen (N) losses from combustion, which could have reduced N availability in the SOM and may explain the observed increase with depth in peat C_{org} (Figure 3). However, the positive charcoal effect on C_{org} was

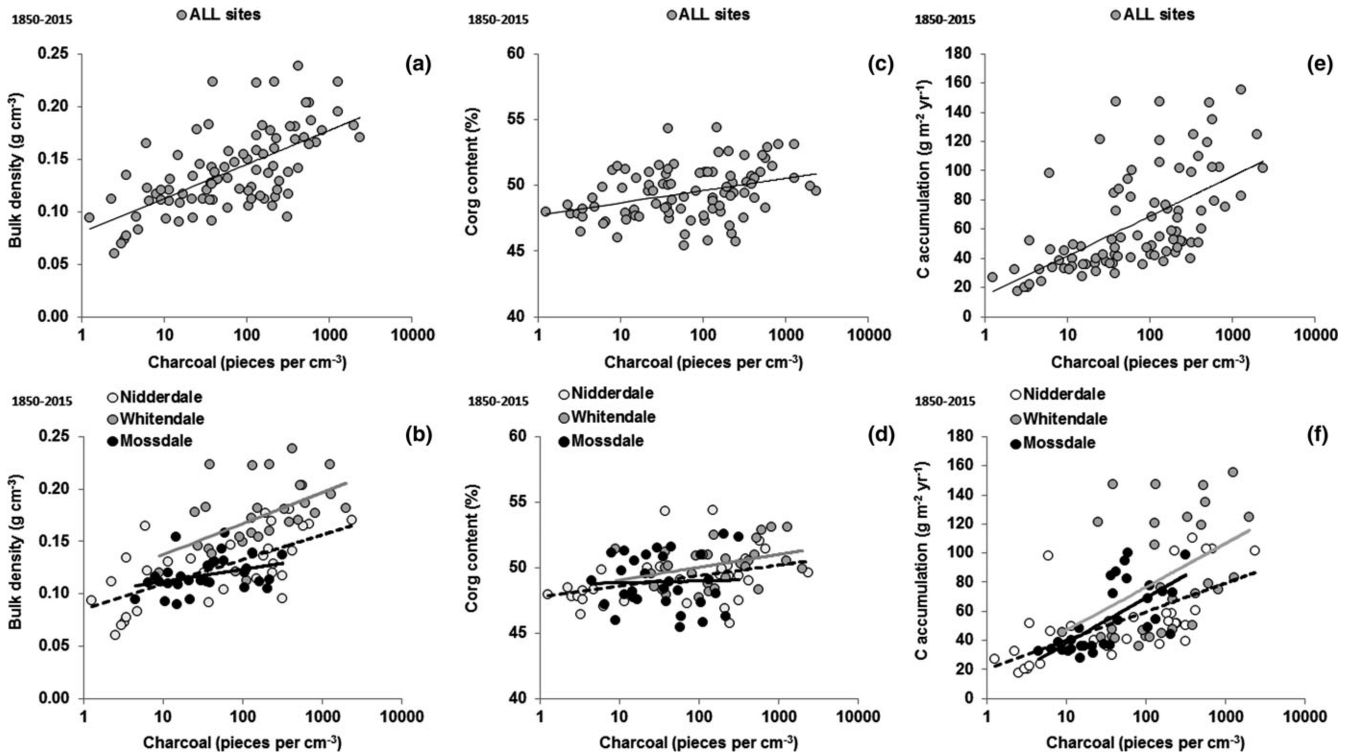

FIGURE 7 Bulk density (left), organic carbon (C_{org}) content (middle) and carbon accumulation (right) versus the natural logarithm of the number of charcoal pieces per cm^3 of peat (concentration) from the top 15 cm (i.e., equal to the spheroidal carbonaceous particle based age range of 1850–2015) of the three peat cores (in 0.5 cm sections) shown for all sites combined (a, c, e) and for individual sites Nidderdale, Mossdale and Whitendale (b, d, f). The best fit logarithmic functions are shown for combined data (thin black line) and for the individual sites (thick lines) with Nidderdale (dashed black), Whitendale (grey) and Mossdale (black). For individual equations and statistics for the regressions per site, see the summary Table 2.

very weak for the top 15 cm and disappeared in the overall core analysis. Possibly the weaker overall C_{org} relationship with charcoal reflected an increasingly difficult direct link between the two parameters with depth (and thus time), as they were measured in two separate peat samples. The increased BD observed at the more frequently burnt sites Nidderdale and Whitendale (supporting hypothesis 1) likely reflected charcoal and ash particles filling the peat pore space. This change in soil chemical and physical peat properties (i.e., increased BD) resulted in the observed higher C accumulation rates at the more frequently burnt sites overall (supporting hypothesis 2; Figure 4) and over the three management-related periods (Figure 6). In fact, mean C accumulation rates (2015–1950) of 3.2 t CO_2 ha^{-1} $year^{-1}$ (87 g C m^{-2} $year^{-1}$) were very similar to the 3.8 t CO_2 ha^{-1} $year^{-1}$ as reported previously by Evans et al. (2014) for unburnt management based on data presented by Garnett et al. (2000). This was unexpected as, so far, one major plot-level study assessing burn rotation effects on peat C accumulation rates found a considerable C loss of -1.1 t CO_2 ha^{-1} $year^{-1}$ under burning over a similar time period (cf. supplementary material in Evans et al. (2014) based on data by Garnett et al. (2000)). However, alongside Clay et al. (2010), we note some potential methodological issues in the Garnett et al. (2000) study: BD samples were only dried for 24 hours, C_{org} was assumed to have a constant value of 50%, and SCP preparation methods could have hindered particle identification. In addition, their reported charcoal layers did not agree with the oldest burn date (i.e., the onset of the experimental burn rotation in 1954 on all plots; cf. Figure 3 in Garnett et al., 2000). In fact, none of the depth profiles in Garnett et al. (2000) show the expected SCP peak around 1975, but all show a clear and high charcoal peak at about 10–11 cm depth. Notably, Garnett et al. (2000) did not consider this disagreement between SCP and charcoal dates in their age–depth determination, although the charcoal peak at 10–11 cm most likely indicated the year 1954 (i.e., the onset of the experiment). Together, these uncertainties mean that the peat C accumulation rates may have been more similar between burnt and unburnt plots than was suggested by Garnett et al. (2000).

The disagreement between burn frequencies (Table 1) and C accumulation (Figure 6) in the mid period (1950–1850) for Mossdale versus Whitendale could reflect methodological challenges; as charcoal concentrations were very low for Mossdale in layers older than 1850 (Figure 5), and depth layers are also closer together (thinner), accurate charcoal peak detection and separation as well as dating became less reliable. Ideally larger peat volumes should be considered for charcoal

TABLE 3 Peat core analysis: peat depth 0–25 cm. Regression model statistics for peat and carbon accumulation rates, carbon content and bulk density against the natural log (ln) transformed charcoal concentrations over the entire 25 cm peat core section (equal to the period 1700–2015) for 0.5 cm section samples (i.e., $n = 50$ per site; degrees of freedom were $n - 2$) shown in Figure 8 (either for all sites combined or the three individual sites). Note that for carbon accumulation only the section 0–24.5 cm could be calculated (i.e., $n = 147$ for all sites or $n = 49$ for individual sites).

x versus *y* regression parameters	*p* Value	Significance	Adj. R^2	*n*	Regression equation
All sites combined					
x(ln charcoal) ~ *y*(carbon accumulation)	<0.0001	***	0.32	147	$y = 8.239x + 26.928$
x(ln charcoal) ~ *y*(peat accumulation)	<0.0001	***	0.16	150	$y = 0.005x + 0.065$
x(ln charcoal) ~ *y*(carbon content)	0.2707	NS	0.00	150	$y = 0.049x + 50.028$
x(ln charcoal) ~ *y*(bulk density)	<0.0001	***	0.38	150	$y = 0.011x + 0.091$
Mossdale					
x(ln charcoal) ~ *y*(carbon accumulation)	<0.0001	***	0.29	49	$y = 6.016x + 31.087$
x(ln charcoal) ~ *y*(peat accumulation)	0.0002	***	0.24	50	$y = 0.008x + 0.064$
x(ln charcoal) ~ *y*(carbon content)	0.3376	NS	0.00	50	$y = -0.162x + 49.950$
x(ln charcoal) ~ *y*(bulk density)	0.0014	**	0.18	50	$y = 0.005x + 0.099$
Nidderdale					
x(ln charcoal) ~ *y*(carbon accumulation)	<0.0001	***	0.35	49	$y = 6.359x + 29.868$
x(ln charcoal) ~ *y*(peat accumulation)	0.0002	***	0.25	50	$y = 0.004x + 0.067$
x(ln charcoal) ~ *y*(carbon content)	0.6263	NS	−0.02	50	$y = 0.069x + 49.575$
x(ln charcoal) ~ *y*(bulk density)	<0.0001	***	0.40	50	$y = 0.009x + 0.093$
Whitendale					
x(ln charcoal) ~ *y*(carbon accumulation)	0.0002	***	0.24	49	$y = 12.904x + 10.783$
x(ln charcoal) ~ *y*(peat accumulation)	0.0080	**	0.12	50	$y = 0.008x + 0.050$
x(ln charcoal) ~ *y*(carbon content)	0.0858	NS	0.04	50	$y = -0.439x + 53.797$
x(ln charcoal) ~ *y*(bulk density)	<0.0001	***	0.32	50	$y = 0.016x + 0.082$

Significance boundaries are NS (non-significant), and considered significant at *$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$.

extractions and ^{14}C or lead isotopes could be deployed to resolve the age resolution, although the reliability of the radiocarbon method becomes limited nearer the peat surface (e.g., Garnett, 1998) and lead isotopes can be unreliable in peat, partly due to plant-derived isotope inputs (e.g., Olid et al., 2008). The lower but still relatively high fire frequencies of every 31 years (across all sites) before the intensification of grouse shooting (Table 1) could indicate that rotational burning was already used to encourage livestock grazing (but no data are available in this respect). However, for the Forest of Bowland (Whitendale), past high fire frequency has previously also been indicated by high and frequent charcoal counts (Mackay & Tallis, 1996).

A comparison of the peat C accumulation rates reported here with published data from other peatland sites over corresponding time periods (see Table 4) revealed very good agreement, particularly when comparing this study with other blanket bog studies (Billett et al., 2010; Garnett, 1998; Hardie et al., 2007). C accumulation rates in these studies are generally much higher during the most recent periods (about 50–100 g C m^{-2} year^{-1}), reflecting highly undecomposed peat, whereas long-term accumulation rates for older layers are about 30 g C m^{-2} year^{-1}. Notwithstanding the overall good agreement in accumulation rates, slope impacts on peat depth and C accumulation (see Heinemeyer et al., 2010) are often ignored. However, slopes of 3–10° in our study are likely comparable in relation to the Garnett et al. (2000) study describing it as a "gentle" slope (in agreement with the figure provided in Garnett's (1998) thesis, i.e., Plate 4.1, p. 90), implying a slope of around 5–10°). We also acknowledge that burnt areas are located within their own topography and greater slopes than in this study could possibly lead to high erosion, particularly under a very frequent burn rotation.

All three sites showed a long burn history. The more frequently burnt and more modified (e.g., drier with lower water tables and less *Sphagnum* spp. moss cover) sites Nidderdale and Whitendale showed higher C accumulation overall (Figure 4). While both sites also showed higher C accumulation than Mossdale in the oldest period (1700–1850), Whitendale was also highest in the other two periods (Figure 6). However, the least modified (e.g., wetter with higher water tables and

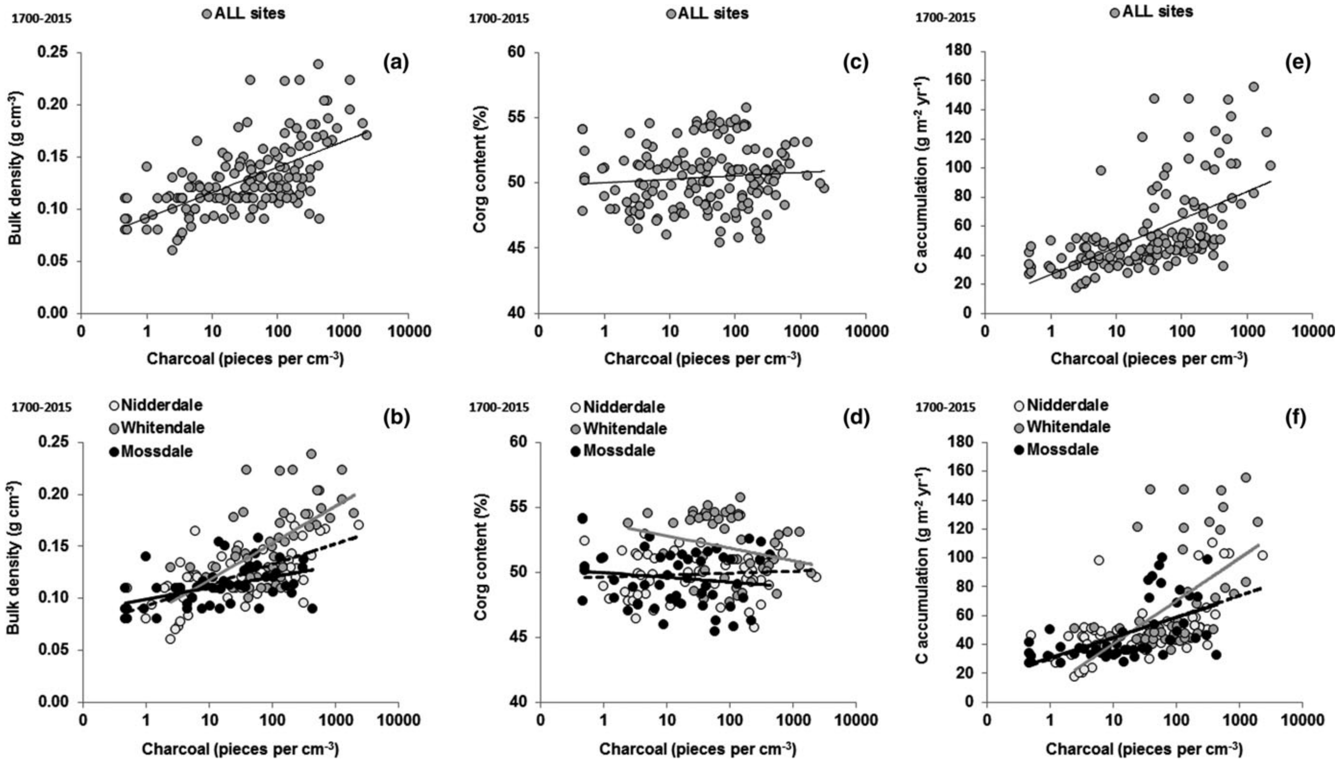

FIGURE 8 Bulk density (left), organic carbon (C_{org}) content (middle) and carbon accumulation (right) versus the natural logarithm of the number of charcoal pieces per cm^3 of peat (concentration) from the top 25 cm (i.e., equal to the spheroidal carbonaceous particle based age range of 1700–2015) of the three peat cores (in 0.5 cm sections) shown for all sites combined (a, c, e) and for the individual sites Nidderdale, Mossdale and Whitendale (b, d, f). The best fit logarithmic functions are shown for combined data (thin black line) and for the individual sites (thick lines) with Nidderdale (dashed black), Whitendale (grey) and Mossdale (black). For individual equations and statistics for the regressions per site see the summary Table 3.

most *Sphagnum* cover) site Mossdale showed less C accumulation (although burn frequency was equally high for Mossdale and Whitendale during 1850–1950; Table 1). Three processes could explain this: (1) burning converted otherwise decomposable heather biomass C into "inert" charcoal (about 5% of standing heather biomass ~18 g C m^{-2} of charcoal; Heinemeyer et al., forthcoming, but similar to estimates by Worrall et al. (2011) of 6.4 g C m^{-2}) or as reported in Clay and Worrall (2011) as 4.3% (of the biomass consumed) in a wildfire; (2) the bulk density increased, possibly due to incorporation of ash and charcoal fragments, thus increasing C stocks; and (3) a potential negative priming effect on decomposition by charcoal (Lu et al., 2014). Notably, this also agreed with the lower C accumulation rates at Nidderdale during 1850–1950 (Figure 6), a period which showed reduced burn frequencies (Table 1) and overall low charcoal counts (Figure 5) at this site. However, the currently anticipated concept that burning over time leads to a decline in peat C stocks, which is largely based on one peatland study (i.e., Garnett et al., 2000; and in parts Ward et al. 2007 for the same experimental plots), as highlighted by Evans et al. (2014), does not agree with this study, which observed considerable C accumulation during grouse moor management periods (Figure 6) which was also positively related to burn frequencies (Table 1).

However, the conclusions reached here are based on a C-stock inventory which could be different compared with using a C-flux approach. Indeed such discrepancies between flux and stock approaches in determining ecosystem C accumulation rates for peatlands have been highlighted previously by Ratcliffe et al. (2017) and Clay et al. (2010). The major disadvantages of the C-flux approach are that it does not capture long-term incorporation of C as charcoal (Clay et al., 2010), while capturing decomposition from deeper, older layers, which affects the C budget calculations of recent periods, due to the mixed age of the overall decomposition signal. The major disadvantages of the C-stock approach are that it relies on uncertain dating techniques (particularly when using only one dating tool, such as SCPs, as in our study) and considers sections of peat separately, which ignores incorporation of surface C into deeper sections through roots and changes in decomposition rates over time. These methodological uncertainties and discrepancies between these approaches require further research in order to obtain greater confidence in long-term ecosystem C sequestration rates in relation to both climate and management, particularly in peatlands. We also acknowledge that our findings were based on several cores albeit from the same locations. Ideally larger cores would be utilised, enabling all analyses to be done on the same core.

TABLE 4 Comparison of annual carbon accumulation rates (in g C m^{-2}) between the three sites in this study (±*SD*) across several periods with burn frequencies and other sample information compared with published values for peatlands across England and Scotland. Note that the only values which are experimentally derived are from this study, Garnett (1998) and Hardie et al. (2007). Billett et al. (2010) provided a best estimate assuming 50% C content and 98% loss on ignition. Lochnagar is 788 m a.s.l. and has ~1600 mm annual rainfall according to Yang et al. (2002) and Gordon et al. (1998), and may have been burnt (Dalton et al., 2005). A question mark (?) indicates a lack of information in the study. Please note the slightly different table headings for carbon accumulation rates and burn frequencies.

				Carbon accumulation rates between periods		Burn frequencies between periods (every # year)			
Location	**Site type**	**Management**	**Sample ID**	**1950–1970s**	**1865–1950**	**1950–1970s**	**1865–1950**	**Sampling date**	**Source**
Butterburn	Raised mire	NA	BFA	82.2	73.1	NA	NA	1999	Billett et al., (2010) (data from Charman, 2007)
			BFB	119	39.7				
			Mean	100.6	56.4				
Lochnagar	"Alpine" sloping blanket mire	Possible burning/grazing	LAB-A	56.9	39.6	NA	NA	1997	Billett et al. (2010) (data from Yang et al., 2001)
Mossdale	Blanket bog	Prescribed burn	MC3	48.1 ± 6.7	36.1 ± 5.1	30	21	2016/17	This study
Nidderdale	Blanket bog	Prescribed burn	NC3	95.6 ± 19.2	30.5 ± 10.6	15	28	2016/17	
Whitendale	Blanket bog	Prescribed burn	WC3	76.3 ± 5.5	49.2 ± 11.3	15	43	2016/17	
Moor House	Blanket bog	Prescribed burn	MH2		30	10?	?		Garnett (1998) PhD thesis
				Carbon accumulation rates between periods		**Burn frequencies between periods (every # year)**			
Location	**Site type**	**Management**	**Sample ID**	**(1955–end date)**		**1955–2015**		**End date**	**Source**
Mossdale	Blanket bog	Prescribed burn	MC3	74.3 ± 17.8		17		2015	This study
Nidderdale	Blanket bog	Prescribed burn	NC3	74.2 ± 26.7		13		2015	
Whitendale	Blanket bog	Prescribed burn	WC3	117.4 ± 27.7		10		2015	
				Lower/upper estimate					
Moor House	Blanket bog	Prescribed burn	VEG 1	19.6	60.0	10		2005	Hardie et al. (2007)
			VEG 2	82.6	123.0				
			VEG 3	>72.6	>72.6				
			SOIL 1	33.2	88.0				
			SOIL 2	44.6	79.8				
			SOIL 3	30.4	71.0				

5 | CONCLUSION

This study supports the hypotheses that increased charcoal input in relation to past burn frequencies can increase peat long-term SOC accumulation. This highlighted the potential of increased long-term C sequestration on rotationally burnt peatlands, possibly due to BD changes, and revealed implications in relation to discrepancies between the flux and stock approaches in peat C sequestration. However, while the methods of dating using SCPs and sieving for charcoal are validated methods, the authors recognise the uncertainties associated with these methods. Other factors may have also influenced the findings regarding charcoal impacts on C accumulation in relation to burn frequency (e.g., changes in N or vegetation composition and thus litter quality). Moreover, the current study was conducted on fairly flat areas (<5°), excluding steeper slope areas, where erosion on bare ground following burning could result in major C losses. Finally, our results do not allow a comparison to an unburnt scenario and estimates are based on low severity prescribed burns and the impacts of more severe arson or wildfire are likely to differ (i.e., when peat burning occurs), leading to considerable peat depth and thus C loss (e.g., Mackay & Tallis, 1996). Notwithstanding these uncertainties, this study highlights the importance of understanding fire dynamics for SOC dynamics and ecosystem C storage and the need to improve our scientific understanding of the processes and their historical importance to the C cycle. Therefore, we suggest that further study using advanced techniques, such as C dating and core scanning (e.g., X-ray fluorescence and X-ray computer tomography), is crucial, especially to further develop C assessment methods and models. Further research is also needed to assess the wider landscape scale (i.e., topographic range) impact of increased charcoal and ash incorporation on peat hydrology and the potential eco-hydrological feedbacks on decomposition processes, as recently highlighted by Ratcliffe et al. (2017), in addition to potential microbial feedbacks. Finally, any holistic burn impact assessment should ideally be providing comprehensive assessments, including above-ground, hydrological, gaseous and below-ground parameters in estimating catchment C stocks/fluxes (specifically considering the above outlined methodological and topographic limitations in this study).

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ENDNOTES

[1] This peer-reviewed report has been submitted to Defra and will be published in due course, subject to approval.

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